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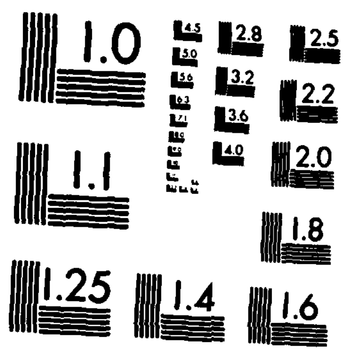

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Shuttle Contamination Modeling: Evolution of Ionized Shuttle Exhaust

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SPACE PHYSICS DIVISION
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"This technical report has been reviewed and is approved for publication"

FOR THE COMMANDER

CHARLES P. PIKE, Chief
Spacecraft Interactions Branch

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Space Physics Division

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We consider the evolution of ionized Shuttle exhaust. While the source of ionization is not treated, the subsequent evolution can be understood in a certain amount of detail. The fundamental conclusions are that: (1) Low-density ions expand with the neutral exhaust for about 100 m where they go through a rapid transition to collisionless behavior and then are swept away (in the Shuttle frame of reference) by the magnetic field, and (2) High-density ions are not affected by the magnetic field and are expected to expand radially away from the Shuttle: neither the ambient ionosphere nor the geomagnetic field can significantly change this behavior. The details of the evolution can be affected by low-level ($\cong$0.1 mV/m) parallel electric fields. The mirror force associated with the geomagnetic field is too weak to have any effect.

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1. INTRODUCTION

One important aspect of the interaction of Shuttle with its environment is the evolution of contaminants and exhaust of Shuttle origin. The purpose of this paper is to provide an order of magnitude survey of the interaction of the exhaust with the ambient environment. The topics considered include the collisional and plasma behavior of the exhaust and the interaction of ionized exhaust with the ambient environment and electromagnetic fields. While the sources of ionization are not treated, the subsequent evolution is treated in a certain amount of detail.

The focus of the paper is the evolution of ionized exhaust. In particular, the goal is to specify the trajectory of the ionized exhaust and to determine the magnitude of the effects of ambient electric and magnetic fields. We will examine the behavior of exhausts with low and high fractional ionization and discuss the qualitative differences in their evolution. The fundamental conclusions are that: (1) Low density ions expand with the neutral exhaust for about 100 m where they go through a rapid transition to collisionless behavior and then are swept away (in the Shuttle frame of reference) by the geomagnetic field, and (2) High density ions are not affected by the magnetic field and are expected to expand radially away from the Shuttle; neither the ambient atmosphere nor the geomagnetic field can significantly change this behavior. The details of the evolution can be affected by low level ($\approx$ 0.1 mV/m) parallel electric fields.

The motive of the paper is to identify some of the physical issues that must be dealt with in an effort to model contamination processes on Shuttle and other large spacecraft. The release of Shuttle exhaust has several possible ways of contributing to the contaminant environment. Among them are (1) direct contamination of Shuttle surfaces and sensors; (2) obscuration of the field of view of sensors, principally by infrared absorption

(Received for publication 13 November 1985).

and (3) optical contamination by glow associated with excited or ionized atoms. While our discussion could be applied to all three categories, we are directly concerned only with the third. The nature of our inquiry is: What is the spatial evolution of Shuttle exhaust, assuming that it is partially ionized? The intent is to be able to outline the physical parameters necessary to determine the evolution and motion of an ion cloud.

Despite the fact that we are able to analyze the motion to a certain extent, the importance of the results is that they point out the physical basis for modeling the behavior and evolution of the exhaust. As such, the present paper should be viewed not as a complete analysis of the problem, which, in fact, it is not intended to be, but as a starting point for such an analysis. We believe that the proper treatment of such phenomena as Shuttle exhaust and contamination requires computer simulation. Yet much of the behavior is quantifiable using analytical methods. It is our feeling that aspects of the behavior should be incorporated into the computer program where possible, rather than modeled by purely numerical methods.

The text is organized into separate sections. The plan of each section is to give (1) a sequence of order-of-magnitude estimates designed to focus on one aspect of the problem, followed by (2) a discussion designed to help develop a coherent argument. A separate discussion section at the end of the paper draws from the conclusions of each section.

2. THE EXHAUST

The purpose of this section is to address the neutral properties of the Shuttle exhaust: composition, fluid properties, and collisional behavior of both neutrals and ions. In addition, we discuss simple properties of the collisional interaction of the exhaust with the neutral atmosphere. We will be primarily interested in the distances from the Shuttle at which transitions from one type of behavior to another occur (for example, from collisional to collisionless behavior).

The molecular composition of the Shuttle RCS exhaust (Bareiss et al,[1] p. E-15) is given in Table 1:

Table 1. Chemical Properties of Shuttle RCS Engine Exhaust

Molecule	Atomic Number	Mole Fraction	Ionization Energy(eV)	$\gamma = \frac{c_p}{c_v}$
H_2O	18	0.33	12.6	1.3
N_2	28	0.31	15.58	1.4
CO_2	44	0.036	13.8	1.3
H_2	2	0.17		1.4
CO	28	0.13	14.0	1.4

1. Bareiss, L.E., Jarossy, F.J., Pizzicaroli, J.C., and Owen, N.L. (1981) Shuttle/Payload Contamination Evaluation Program: The SPACE Computer Program User's Manual, Martin Marietta Corp., Denver.

From Table 1, it follows that the mean molecular weight is $A \simeq 16$. For purposes of estimating orders of magnitude, we will use $A = 16$. γ is the ratio of specific heats for each molecular species. The mean value of γ is slightly less than 1.4; we will use 1.4 as a typical value.

The exhaust of the thrusters has a velocity $V \simeq 3\,\mathrm{km/sec}$ relative to the orbiter and a temperature $T \simeq 3000°\mathrm{K}$; the flux of the exhaust is given by

$$\rho V = \frac{1351}{r^2} \cos (0.01260\theta)^{10} \ \mathrm{gm/(cm^2 sec)} \text{ for } \theta < 64° \tag{1}$$

$$\rho V = \frac{35}{r^2} \exp \ -0.035(\theta - 64) \ \mathrm{gm/(cm^2 sec)} \text{ for } \theta > 64°$$

where θ is in degrees and r is in cm.[2] The flux is plotted in Figure 1.

To obtain order-of-magnitude estimates for the fluid and collisional properties of the exhaust, we will assume that the exhaust expands at constant velocity:

$$V = 3\,\mathrm{km/sec} = \text{constant.} \tag{2}$$

From the mass flux of the neutral exhaust

$$\rho V \simeq \frac{1350}{r^2} \ \mathrm{gm/(cm^2 sec)} \tag{3}$$

one can then compute the mass density

$$\rho = \frac{1350}{Vr^2} = \frac{4.5 \times 10^{-3}}{r^2} \ \mathrm{gm/cm^3} \tag{4}$$

and the number density

$$n = \frac{1350}{Am_H Vr^2} \tag{5}$$

$$= \frac{2.7 \times 10^{21}}{Ar^2} \ \mathrm{cm}^{-3}$$

2. Ehlers, H. Private communication.

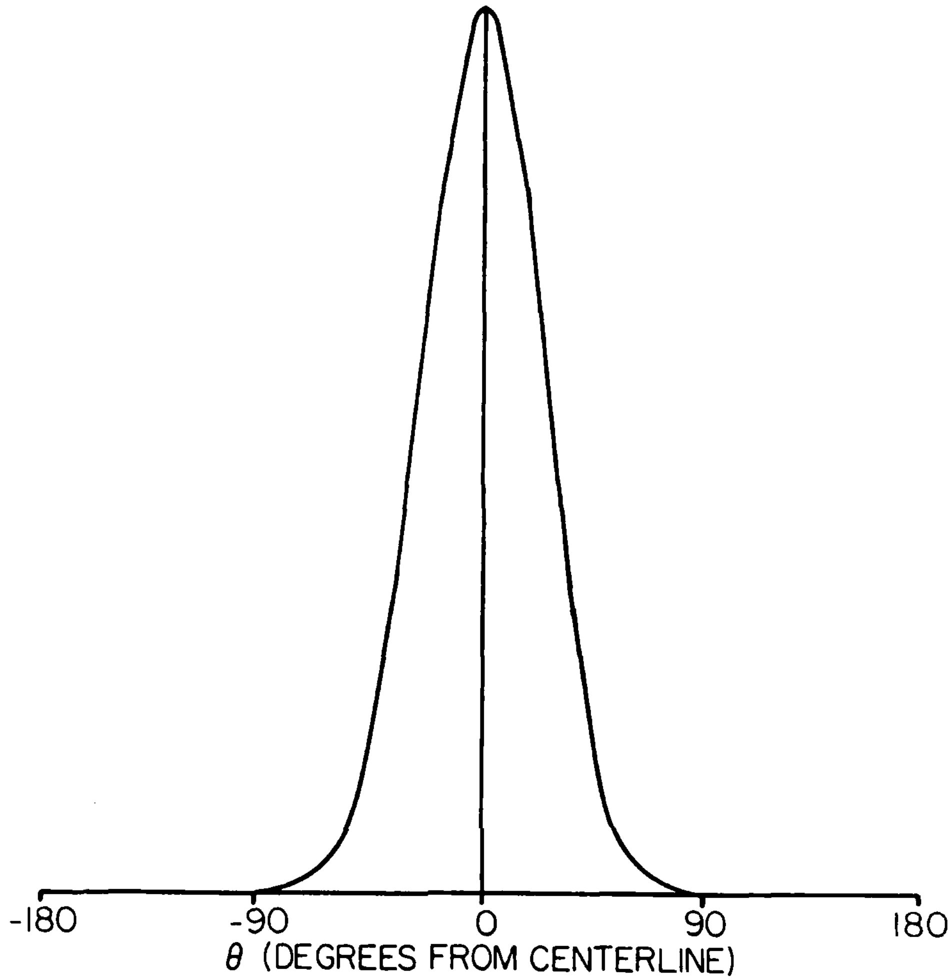

Figure 1. Flux Profile of Shuttle RCS Exhaust: Flux vs Angle

where m_H is the mass of hydrogen. The qualitative behavior of the temperature can then be obtained by assuming adiabatic expansion:

$$T = T_0\left(\frac{n}{n_0}\right)^{\gamma - 1} \qquad (6)$$

$$\sim r^{-2(\gamma - 1)}$$

$$\sim r^{-0.8}$$

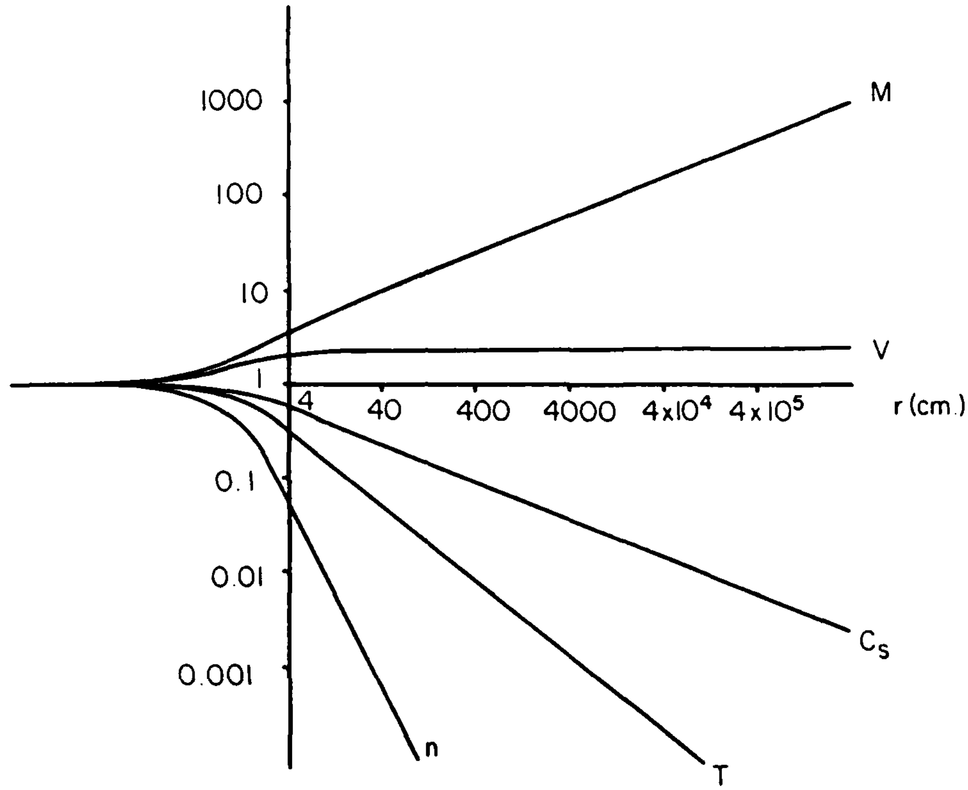

Figure 2. Characteristic Behavior of Mach Number, Bulk Velocity, Sound Speed, Temperature, and Number density as Functions of Distance From Nozzle

More detailed results are shown in Figure 2. These results, for $\gamma = 1.4$, were computed for adiabatic expansion through a de Laval nozzle of 4-cm diameter. Because the de Laval model used is essentially one-dimensional, the results are only qualitative, but they do indicate the characteristic variations associated with adiabatic expansion. The variables plotted are the velocity V, the sound speed $c_s = \sqrt{\gamma kT/m}$, the Mach number V/c_s, the temperature T, and the number density n. They are all normalized to their values at the supersonic transition at the throat of the nozzle. They are plotted as functions of distance from the throat.

For the number density given by Eq. 5, the mean free path for neutral collisions

$$\lambda = \frac{1}{n\sigma} \tag{7}$$

with a cross section typical of atomic dimensions

$$\sigma = 4\pi \times 10^{-16}\mathrm{cm}^2 \tag{8}$$

is

$$\lambda = 3.0 \times 10^{-7} A r^2 \mathrm{cm}. \tag{9}$$

The distance at which the mean free path is equal to the scale height $L \sim \frac{r}{2}$ is

$$r \simeq \frac{17}{A}\,\mathrm{km}. \tag{10}$$

For A = 16, this is about 1 km. This suggests that the strongest interaction between ambient molecules (including atoms and ions) and exhaust molecules occurs at about 1 km. Outside this distance, the exhaust is so tenuous that collisions with ambients are rare. Inside this distance, the collisional mean free path is small enough that ambients can penetrate only with difficulty. This is clearly only an order-of-magnitude estimate; the details of the penetration depend on the relative velocities and the angle at which the ambients enter the exhaust. In particular, ambient flux impinging on the sides of the exhaust cone will have a strong interaction over about a mean free path, which is short near the nozzle. Similar arguments can be developed for the exhaust outside the main plume. There the mass flux is

$$\rho V \sim \frac{35}{r^2}\,\frac{\mathrm{gm}}{(\mathrm{cm}^2\mathrm{sec})} \tag{11}$$

and the distance where the mean free path is equal to the scale height is about 30 m.

An important consequence of the collisional behavior of the exhaust is that ions in the exhaust are necessarily swept out with the exhaust until a transition to a collisionless regime is reached. To anticipate the results of the next section, the gyroperiod of an ion with a velocity equal to that of the thruster is about 1.6×10^{-3} A sec (for singly ionized ions). The mean free time of a thermal ion is

$$\tau = \frac{1}{(n\sigma w)} \tag{12}$$

where w is the thermal speed of the exhaust:

$$w = \sqrt{\frac{2kT}{m}} \tag{13}$$

and k is Boltzmann's constant. The distance at which the mean free time is equal to the gyroperiod is

$$r \approx \frac{400}{\sqrt{M}}\, m \tag{14}$$

where $M \equiv V/c_S \sim V/w$ is the Mach number. Up to this distance, *the ion suffers many* collisions per gyroperiod and is swept out by the exhaust. The implication of multiple collisions is that the ions are thermalized in the frame of reference of the exhaust; in the Shuttle frame, an ion moves with the bulk speed of the exhaust plus its thermal motion. After this point, the ion suffers few collisions per gyroradius, and ions in the exhaust follow smooth trajectories in the local electric and magnetic fields. The subsequent behavior of the ions depends on the properties of the plasma rather than the collisional behavior of the neutral gas.

The transition to collisionless behavior is rather abrupt if the exhaust has cooled rapidly. Repeating the above argument while using the fact that the mean free path in the Shuttle frame depends on velocities ranging from roughly $V-w$ to $V+w$, one sees that the range of distances implied by Eq. (14) is

$$r = \frac{400}{\sqrt{(M \pm 1)}}\, m \tag{15}$$

so that the thickness of the transition region for large M is on the order of

$$\Delta r \approx 400 M^{-3/2}\, m \tag{16}$$

From Figure 2, the Mach number (on the assumption of adiabatic expansion) beyond a few meters is about 10 for $\gamma = 1.4$, so the transition distance is about 100 m. The thickness of the transition region on this estimate is therefore of the order of $100/M \approx 10$ m. Since any observed transition is unlikely to be less than a gyroradius thick, a better estimate may be A m for heavy (singly ionized) ions. In any event, it should be noted that the maximum extent of the region occupied by ions is the transition distance plus about one gyroradius (for a total $\sim$ 100 to 110 m) if the ions do not continue to move along with the neutral exhaust.

The Shuttle RCS exhaust is delivered in bursts of 80–300 m sec and the total mass of each burst is $\sim$ 142 gm. The number of particles in each burst is (for $A = 16$)

$$N = 5.3 \times 10^{24}. \tag{17}$$

For purposes of comparison, the number density of the neutral ionosphere is

$$n \sim 10^9 \mathrm{cm}^{-3} \tag{18}$$

so the mass density is

$$\rho \sim 3 \times 10^{-14} \mathrm{gm/cm}^3 \tag{19}$$

The total mass in $1\,\mathrm{km}^3$ of ambient ionosphere is about 3gm. As a result, the exhaust dominates the neutral ionosphere near the Shuttle. The distance at which the neutral ionosphere begins to dominate is where the exhaust mass density has dropped to the neutral ionospheric mass density:

$$r \sim 4\,\mathrm{km} \tag{20}$$

The ionization state of the exhaust is not well known. Results of the computer program CONTAM III, which models the combustion process inside the rocket chamber but does not account for recombination processes during exit, show the number of neutral particles ejected to be $\sim 10^{25}$ and the number of ejected ions to be $\sim 10^{17}$ for a fractional ionization of $\sim 10^{-8}$.[3] This result is consistent with estimates based on the Saha equation (see below, this section). Cooling of the exhaust and recombination processes may decrease the ionization as the exhaust expands. However, for reference purposes, let us take this figure as representative of the state of the exhaust outside the orbiter. The total number of ions released per burst is

$$N_i = 10^{16}. \tag{21}$$

A crude estimate of the minimum volume occupied by the ions in one burst for particles injected along the field is

$$\Xi = \pi \rho^2 V \Delta t \tag{22}$$

where $\rho = 10\,\mathrm{m}$ is the ion gyroradius (based on the ion thermal speed) and Δt is the time

3. Pickett, Jolene S., Murphy, Gerald B., Kurth, William S., and Goertz, Christopher K. (1985) Effects of chemical releases by the STS 3 orbiter on the ionosphere, J. Geophys. Res. 90:3487-3497.

duration of the burst. This assumes that the burst occupies a column of length $V\Delta t$ and cross-section $\pi\rho^2$. The corresponding maximum ion density is

$$n_i \approx \frac{N_i}{\pi\rho^2 V\Delta t} \tag{23}$$

$$\approx 10^5\,\mathrm{cm}^{-3}.$$

If the exhaust is injected across the magnetic field, the maximum number density is

$$n_i \approx \frac{N_i}{2\times\pi\rho^2 w\Delta t} \tag{24}$$

where $\rho \approx 20\,\mathrm{m}$ is the gyroradius based on the velocity, and the extra factor of two accounts for the spreading of the beam in both directions along the field, so that

$$n_i \approx 10^4\,\mathrm{cm}^{-3}. \tag{25}$$

These estimates show that the maximum ion number density from the exhaust is of the same order of magnitude as the ambient ion density ($n_i \sim 10^4\,\mathrm{cm}^{-3}$).

While these estimates establish maximum number densities, they are probably too high for two reasons: (1) The temperature is poorly known, and our estimate may be too high because of adiabatic cooling; (2) The ions will be spread over a large surface at the transition to collisionless behavior. The effect of lowering the temperature is to lower the number of ions in the exhaust by up to many orders of magnitude because of the temperature dependence in the Saha equation. The effect of spreading the ions over the transition layer is to lower the ion density by about one order of magnitude.

The largest uncertainty in establishing the intrinsic ionization state of the exhaust is the uncertainty in the temperature of the exhaust as as function of distance. Even moderate uncertainties in the temperature cause large uncertainties in the fractional ionization. This sensitivity follows from the temperature dependence of the Saha equation

$$f \equiv \frac{n_i}{n_n} \approx 5\times 10^{10}\left(\frac{T^{3/4}}{n_n}\right)\exp\left(\frac{-I}{2kT}\right) \tag{26}$$

where the fractional ionization is defined as the ratio of the number density of ions to that of neutrals, n_n is the number of neutrals per cubic meter, and I is the ionization energy (cf. Chen,[4] p. 1). The striking feature of Eq. (26) is that if the temperature is constant,

4. Chen, F. (1984 Introduction to Plasma Physics, Plenum, New York.

the fractional ionization rises with distance because of the inverse dependence on the neutral density while if the temperature decreases adiabatically, the fractional ionization is essentially zero past a few meters from the aperture.

This extreme sensitivity to the details of the temperature profile leads to the following observation: The nominal composition of the exhaust given in Table 1 may be useless to determine the ionization state of the exhaust. Low level (for example, 1 part in 10^6 or 10^8) contaminants with low ionization potentials, such as metals, would lead to much higher ionization levels than the nominal constituents, assuming that the exhaust expands adiabatically.

A number of important results follow from these order-of-magnitude estimates:

(1) The ions in the exhaust will be swept out with the neutral exhaust for about 100 m. At about 100 m, there is a transition to collisionless behavior; the transition region is on the order of 10 m thick.

(2) The strongest collisional interaction with the ambient atmosphere is about 1 km from the Shuttle. This is the region where neutral collisions would be most likely to cause ionization, if ionization is energetically possible.

(3) The ambient ionosphere cannot have much effect on the trajectory of the neutral exhaust. It simply does not have enough momentum to stop more than an extremely small fraction of the exhaust. As a result, the neutral part of the exhaust can be expected to travel unimpeded through the ambient environment for a distance on the order of 4 km. Even at this distance, the neutral exhaust cannot be deflected by the ambient atmosphere because the mean free path is too large. This behavior could be changed by such processes as charge exchange, which are not considered here.

(4) Reasonably high ionization states are obtained if the exhaust expands isothermally; however, the ionization state is so temperature-dependent that adiabatic expansion means that the nominal exhaust molecules are not ionized past a few meters from the aperture.

3. AMBIENT ELECTRIC AND MAGNETIC FIELDS

An ionized exhaust evolves under the influence of ambient electric and magnetic fields. The magnitude of the effects depends not only on the strength of the ambient fields, but the extent to which the plasma can shield itself from them. The purpose of this section is to determine the order of magnitude of the effects of the ambient fields on the evolution of Shuttle exhaust. The fundamental assumption is that the plasma responds to the fields as a collection of single particles. As a result, we ignore shielding and polarization; they will be discussed in a separate section.

Typical Shuttle altitudes are 300 km. Let us take a typical geomagnetic L-shell to be L = 1.2 and the magnetic field strength to be B = 0.4 G.

For this magnetic field, the gyrofrequency of ions is

$$\Omega_i = \frac{ZeB}{(Am_H c)} \qquad (27)$$

$$= 3800 \left(\frac{Z}{A}\right) \sec^{-1}$$

where Z represents the ionic charge state, e is the proton charge, and m_H is the mass of hydrogen. For A = 16 and Z = 1,

$$\Omega_i = 240\,\mathrm{sec}^{-1} \tag{28}$$

The ion gyroradius for the propulsion velocity V, that is, for the exhaust directed across the field, is

$$\rho_i = \frac{A m_H c V}{(ZeB)} \tag{29}$$

$$= 0.78 \left(\frac{A}{Z}\right) \mathrm{m}$$

or, for A = 16 and Z = 1,

$$\rho_i = 12\,\mathrm{m}.$$

This estimate is appropriate for ions which have been driven by collisions to a collisionless region. The electron gyroradius is

$$\rho_e = \frac{m_e c v}{eB} \tag{31}$$

$$= \frac{\sqrt{2 m_e c^2 \epsilon}}{eB}$$

$$= 8.4 \sqrt{\epsilon (\mathrm{eV})}\ \mathrm{cm}$$

where ϵ is the electron energy expressed in electron-volts. The gyroradius for electrons with energies up to 100 eV is only about 10 cm. For the gyroradius to be as large as 10 m, the electron energy would have to be 10 keV.

The large-scale behavior of charged particles is determined by electric and magnetic forces through the Lorentz force

$$\frac{m d\vec{v}}{dt} = Ze\left(\vec{E} + \frac{\vec{v} \times \vec{B}}{c}\right). \tag{32}$$

The magnetic field effects can be divided into three categories: (1) the perpendicular gyration about the magnetic field line at Ω_i, (2) the acceleration along the field by the mirror force

$$F_{\parallel} = -\mu \nabla_{\parallel} B, \tag{33}$$

and (3) the perpendicular drift across the magnetic field, given by

$$\vec{V}_{\perp} = c\mu \frac{\vec{B} \times \vec{\nabla} B}{eB^2} \tag{34}$$

where $\mu = (1/2)mv_{\perp}^2/B$ is the magnetic dipole moment of the particle. The parallel acceleration of the particle is

$$a_{\parallel} = -\left(\frac{1}{2}\right) v_{\perp}^2 \nabla_{\parallel} \ell n B \tag{35}$$

Note that $a_{\parallel}$ is independent of the mass of the particle and of the magnetic field strength. It depends only on the velocity of the particle and the scale length of the field. For particles ejected perpendicular to the field at $v = 3\,\text{km/sec}$ and using

$$\nabla \ell n B \approx \frac{3}{r} \tag{36}$$

$$\approx \frac{3}{R_e}$$

(where R_e is one Earth radius) for the geomagnetic dipole field, the parallel acceleration is

$$a_{\parallel} \approx 2\,\text{m/sec}^2. \tag{37}$$

The magnitude of the perpendicular drift velocity is

$$V_{\perp} = \left(\frac{v_{\perp}^2}{2\Omega_i}\right) \nabla_{\perp} \ell n B \tag{38}$$

which is, for $A = 16$ and $Z = 1$, with $v_{\perp} = 3\,\text{km/sec}$

$$V_{\perp} \sim 0.9\,\text{cm/sec}. \tag{39}$$

The magnitude of $\vec{V}_\perp$ is so small that it can be ignored altogether.

The above result for mirror acceleration holds for any charged particle, including electrons, ejected at 3 km/sec. The thermal speed of electrons,

$$w \simeq \leq \sqrt{\frac{2kT_{exh}}{m_e}} \tag{40}$$

$$\simeq 300\,\text{km sec}$$

is a more representative velocity of the electrons in the exhaust. The parallel acceleration for this velocity is

$$a_{\parallel} \sim 20\,\text{km/sec}^2 \tag{41}$$

while the perpendicular drift velocity

$$V_\perp \simeq 0.3\,\text{cm/sec} \tag{42}$$

is still negligible. For Eq. (41) to have any significance, it is necessary to assume that the *electrons are free to move away from the ions in the exhaust.*

Plasma processes such as Alfven critical ionization and beam plasma discharge are associated with unstable growth of electrostatic waves which accelerate electrons to energies on the order of 100 eV. In general, the parallel acceleration of electrons is given by

$$a_{\parallel} = 1.8 \times 10^{10} \varepsilon(\text{eV}) \nabla_{\parallel} \ell n B\,\text{km/sec}^2 \tag{43}$$

$$\simeq 83\varepsilon(\text{eV})\,\text{km/sec}^2$$

where ε is the electron energy in electron-volts. *Energetic electrons of 100 eV are accelerated at*

$$a_{\parallel} \simeq 10^4\,\text{km/sec}^2 \tag{44}$$

assuming that charge separation effects are not important.

The rate of loss of energetic electrons by parallel mirror acceleration is limited by ambipolar diffusion. The ambipolar diffusion coefficient is

$$D \approx \frac{k(T_e + T_i)}{n\sigma(m_e w_e + m_i w_i)} \tag{45}$$

where n is the neutral number density (Chen,[4] p. 160). For energetic electrons with

$$T_e \sim \left(\frac{m_i}{m_e}\right) T_i$$

$$D \approx \frac{w_e}{n\sigma}.$$

The time scale for diffusion losses is

$$\tau_d \sim \frac{L^2}{D} \tag{46}$$

where L is a typical scale length in the problem. Diffusion is important only if τ_d is short compared to a convection time:

$$\tau_c = \frac{L}{V}. \tag{47}$$

The ratio of diffusion time to convection time is

$$\frac{\tau_d}{\tau_c} \sim \frac{LVn\sigma}{w_e}. \tag{48}$$

Taking L ~ r and using Eq. (5), we have

$$\frac{\tau_d}{\tau_c} \sim \frac{1.1 \times 10^3}{r\sqrt{\epsilon(eV)}}. \tag{49}$$

The distance outside of which diffusion dominates convection (that is, $\tau_d/\tau_c < 1$ is)

$$r \geq \frac{1.1 \times 10^3}{\sqrt{\epsilon(eV)}}\ \mathrm{m}. \tag{50}$$

So, for radii greater than about 1 m to perhaps 100 m, ambipolar diffusion of energetic electrons is dominant and geomagnetic mirror acceleration is an effective process for removal of electrons and ions.

The effective velocity associated with removal of charged particles by ambipolar diffusion can be estimated by equating an effective mass flux to the diffusion flux:

$$\rho \vec{V}_{eff} \cong D\vec{\nabla}\rho \tag{51}$$

or

$$\frac{V_{eff}}{V} \sim \frac{D}{(LV)} \sim \frac{\tau_c}{\tau_d}. \tag{52}$$

Near the spacecraft, the effective diffusion velocity is of the same order of magnitude as the flow velocity.

A charged particle injected into the geomagnetic field has a bounce motion associated with the mirror acceleration because, aside from slow drifts, the particle moves along a given field line and mirrors at each end. For a sufficiently low bounce period, particles mirroring in the opposite hemisphere could possibly return to the spacecraft, affecting the nature of the interaction. While such a result appears to be unlikely a priori, we analyze it in the following manner: The bounce period is roughly the local radius divided by the particle velocity (Schulz and Lanzerotti,[5] p. 18):

$$\frac{2\pi}{\Omega_B} \approx \frac{3.5r}{v} \tag{53}$$

where the factor 3.5 is appropriate for a mirror latitude of 23°, typical of the Shuttle in low inclination orbit. The bounce period for a 3 km/sec particle is about 7000 sec. The bounce time of a nonrelativistic electron is

$$\tau_B \approx \frac{50}{\sqrt{\epsilon(eV)}}\ \text{sec}. \tag{54}$$

The bounce period of a 100 keV electron is therefore about 4 sec. These bounce periods are so long that we conclude that they bear no likely relation to the Shuttle interaction.

An important question in our analysis is the depth into the ionosphere to which a charged particle penetrates as a result of the mirror acceleration for a given velocity. The reason for raising this question is to investigate possible asymmetries due to the interaction of an ionized cloud with the geomagnetic field. This can be answered approximately based on simple one-dimensional motion arguments. If the initial velocity and constant acceleration are $v_{\parallel 0}$ and $a_\parallel$, then the penetration depth in the direction along the field opposing the acceleration is

$$s = \frac{v_{\parallel 0}^2}{2a_\parallel}. \tag{55}$$

5. Schulz, M., and Lanzerotti, L.J. (1974) Particle Diffusion in the Radiation Belts, Springer-Verlag, Berlin.

Using Eq. (35) for the parallel acceleration, the penetration depth is approximately

$$s = \frac{v_0^2}{v_{10}^2 \nabla \ell n B} \tag{56}$$

$$= \frac{\mathrm{ctn}^2 \alpha}{\nabla \ell n B}$$

where α is the initial pitch angle (the angle between the initial velocity and the magnetic field). It is clear that particles with any significant component of velocity in the mirror direction (toward the nadir) will travel a reasonable fraction of an earth radius in that direction. For example, particles that deviate from a pitch angle of 90° by more than 0.05° will penetrate more than 1 km toward the nadir.

The effect of large-scale electric fields can be divided into two categories: (1) parallel electric fields, $E_{\|} = \vec{B}(\vec{B}\cdot\vec{E})/B^2$, and (2) perpendicular electric fields, $\vec{E}_{\perp} = \vec{E} - \vec{E}_{\|}$. The effect of a parallel electric field is to accelerate the particle along the magnetic field at the rate

$$a_{\|} = \frac{ZeE}{Am_H} \tag{57}$$

For ions

$$a_{\|} \approx 9.6 \times 10^4 \left(\frac{Z}{A}\right) E_{\|}(\mathrm{V/m})\,\mathrm{km/sec}^2 \tag{58}$$

and for electrons

$$a_{\|} \approx 1.8 \times 10^8 E_{\|}(\mathrm{V/m})\,\mathrm{km/sec}^2. \tag{59}$$

For purposes of illustration, an ion with $A = 16$ and $Z = 1$ is accelerated in a field $E_{\|} = 1$ mV/m to a velocity of

$$v_{\|} = 6\,\mathrm{km/sec} \tag{60}$$

in 1 sec. During this time interval, the path length, starting from $v_{\|} = 0$, is

$$s \approx 3\,\mathrm{km}. \tag{61}$$

The corresponding figures for electrons are

$$v_{\parallel} = 1.8 \times 10^5 \,\text{km/sec} \tag{62}$$

and

$$s = 8.8 \times 10^4 \,\text{km}. \tag{63}$$

The perpendicular electric field causes an $E \times B$ drift which is the same for electrons and ions:

$$\vec{V}_{\perp} = \frac{c\vec{E} \times \vec{B}}{B^2}. \tag{64}$$

This drift is perpendicular to both $\vec{E}$ and $\vec{B}$; its magnitude is

$$V_{\perp} \approx 25 E_1 (\text{V/m}) \,\text{km/sec}. \tag{65}$$

The velocity in a 1 mV/m electric field is 0.25 km/sec.

An illustrative parameter in determining the relative effect of electric and magnetic accelerations is the parallel electric field, $E_{\parallel}'$, which is equivalent to the mirror acceleration. This electric field is determined by the equality

$$\frac{ZeE_{\parallel}'}{Am_H} = \left(\frac{1}{2}\right) v^2 \nabla_{\parallel} \ln B \tag{66}$$

or, for ions,

$$E_{\parallel}' = Am_H v^2 \frac{\nabla_{\parallel} \ln B}{2Ze} \tag{67}$$

$$\approx 2.2 \times 10^{-8} \frac{A}{Z} \,\text{V/m}$$

for $v = 3$ km/sec. For electrons

$$E_{\parallel}' = \left(\frac{\varepsilon}{e}\right) \nabla_{\parallel} \ln B \tag{68}$$

$$= 4.7 \times 10^{-7} \varepsilon(\text{eV}) \text{ V/m}$$

Parallel electric fields are not measured to be greater than 1 mV/m below 1500 km.[6] They cannot be measured at all below about 1 mV/m. For our purposes, we would like to estimate the order of magnitude of the maximum electric field at low altitudes.

In a static atmosphere, the electric field is determined by

$$\vec{\nabla} P_i = n_i e\vec{E} + n_i m_i \vec{g} \tag{69}$$

$$\vec{\nabla} P_e = -n_e e\vec{E} + n_e m_e \vec{g} \tag{70}$$

and

$$\vec{\nabla}\cdot\vec{E} = 4\pi e(n_i - n_e) \tag{71}$$

where $\vec{g}$ is gravitational acceleration. From the difference of Eqs. (69) and (70)

$$\vec{E} = \left(\frac{1}{2} ne\right)[\vec{\nabla}(P_i - P_e) - nm_i\vec{g}] \tag{72}$$

we have

$$E \approx \frac{nkT}{(2neL)} - \frac{m_i g}{(2e)} \tag{73}$$

where $T \approx 1000°$ K is the temperature of the ionosphere. It is apparent that E cannot be much larger than the largest of kT/(2eL) and $m_i g/(2e)$ or about 10^{-7} V/m. Extremely small electric fields, well below measurable thresholds, can have a larger effect on parallel acceleration than the geomagnetic mirror force.

This pressure balance argument ignores motion. The electric field due to motion of the ionosphere (due to frictional coupling of the ions to neutral winds) is

$$\vec{E} = -\left(\frac{1}{c}\right)\vec{V} \times \vec{B} \tag{74}$$

where $\vec{V}$ is the velocity of the plasma in the frame of the earth. Taking a velocity of

6. Maynard, N. Private communication.

0.1 km/sec the maximum electric field is of the order of 0.002 V/m. This is a perpendicular electric field and contributes only to perpendicular drifts. This electric field can be neglected in comparison with the electric field induced by the Shuttle motion (see below).

As well as large-scale electric fields intrinsic to the plasma, the electric field due to the motion of the spacecraft should be mentioned. If the electric field in the frame of the plasma is zero, then the motion of the plasma as measured in the spacecraft frame

$$\vec{U} = -\vec{V}_{sc} \tag{75}$$

where $\vec{V}_{sc}$ is the spacecraft velocity measured in the plasma frame, will cause an electric field

$$\vec{E} = -\left(\frac{1}{c}\right)\vec{U}\times\vec{B}. \tag{76}$$

This electric field is just such as to cause the plasma to $E \times B$ drift at the velocity

$$\vec{U} = \frac{c\vec{E}\times\vec{B}}{B^2} \tag{77}$$

in the spacecraft frame. The Shuttle velocity is $U = 7.3$ km/sec and the associated electric field is 0.2 V/m. Any ambient perpendicular electric fields would have to be of order 0.2 V/m to have a significant effect.

From the above estimates, we learn the following:

(1) The geomagnetic mirror force is insufficient to influence the behavior of ions or electrons; it is far too small. In addition, we may make the following observation: any thermal process (critical ionization, for example) which produced large numbers of ions would be expected to produce an isotropic plasma, at least as far as the direction of the field is concerned. Consequently, as many ions or electrons would travel down the field line as up because the mirror force cannot turn them within a significant fraction of an Earth radius.

(2) The behavior of ions and electrons can be influenced significantly by relatively low level ($\simeq$0.1 mV/m) parallel electric fields. The accelerations and resulting velocities are on the same order of magnitude as velocities resulting from the motion of Shuttle.

(3) The order of magnitude of the parallel electric fields required is much smaller than can be measured experimentally but probably larger than can be reasonably expected at low altitudes.

(4) Ambient perpendicular electric fields are not expected to have any significant influence on the evolution of ionized contaminants as observed in the frame of reference of Shuttle.

(5) The geomagnetic bounce time is probably too long to have any effect on short-lived ($\simeq$ 1 sec) Shuttle exhaust phenomena.

4. MACROSCOPIC PLASMA BEHAVIOR

The interaction of the plasma and electric and magnetic fields depends on the density of the plasma. The behavior of tenuous and dense plasmas is essentially different. Tenuous plasmas, for which the rest mass energy density is much less than the magnetic energy density, tend to behave like a collection of single particles in the external magnetic field. On the contrary, dense plasmas, for which the rest mass energy density is much greater than the magnetic field energy density, tend to shield any external electric field and move across magnetic field lines. In addition, plasmas whose thermal energy density is much less than the magnetic energy density do not significantly change the magnetic field while the diamagnetic effects of a plasma whose thermal energy density greatly exceeds the magnetic energy density strongly perturb the external field.

The single particle behavior is governed by the plasma dielectric constant

$$\kappa = \frac{4\pi\rho c^2}{B^2} \tag{78}$$

(see Schmidt[7]). This is the ratio of the rest mass energy density to the magnetic energy density. It can also be thought of as $c^2/V_A{}^2$, where V_A is the (nonrelativistic) Alfven speed, or as the square of the ratio of the plasma frequency to the ion gyrofrequency:

$$\kappa = \frac{\omega_p{}^2}{\Omega_i{}^2}. \tag{79}$$

Single particle behavior is determined by $\kappa << 1$. If $\kappa >> 1$, the plasma cloud polarizes in such as way that the electric field in the center of mass frame (the proper frame of the plasma) vanishes and the momentum of the cloud is conserved independently of the external magnetic field. This means that the initial momentum of the plasma cloud, which is determined by the momentum of the exhaust, is conserved.

Using the values of the exhaust density [Eq. (4)], the dielectric constant is given by

$$\kappa = 3.2 \times 10^{20} \frac{f}{r^2} \tag{80}$$

where f(r) is the fractional ionization of the exhaust and r is in cm. The distance at which $\kappa \approx 1$ is

$$r \approx 1.8 \times 10^5 \sqrt{f}\,\mathrm{km} \tag{81}$$

7. Schmidt, George. (1979) Physics of High Temperature Plasma, Academic Press, New York.

If there is strong ionization (for example, $f \sim 1$), then the plasma polarizes strongly to a distance on the order of 10^5 km and does not follow the magnetic field. On the other hand, single particle behavior, for which the particles follow the ambient magnetic field lines, past about 10 m requires

$$f \sim 10^{-12}. \tag{82}$$

Any observation which showed ions travelling along the ambient magnetic field would suggest that the ionization state was extremely weak. The actual ion density implied by Eq. (82) is about $1\,\mathrm{cm}^{-3}$.

The diamagnetic effect of the plasma on the magnetic field is determined by the plasma β:

$$\beta = \frac{8\pi P}{B^2}. \tag{83}$$

If $\beta << 1$, then the magnetic field is essentially given by the ambient field; while if $\beta >> 1$, then the field is strongly perturbed, essentially killing the field inside the plasma. Then we have

$$\beta = 4.5 \times 10^{10} \frac{f}{(Mr)^2} \tag{84}$$

where M is the Mach number. The distance for which $\beta = 1$ is

$$r = \frac{10\sqrt{f}}{M}\,\mathrm{km} \tag{85}$$

If the plasma is highly ionized, the magnetic field is zero to perhaps 100 m or more, while, if the fractional ionization is on the order of 10^{-12}, the ambient field is essentially undisturbed.

These considerations lead to the following conclusions:

(1) A sufficiently high density plasma will follow the initial trajectory of the exhaust for a large distance. If the exhaust were fully ionized, it would travel a perhaps 10^5 km before it was tenuous enough to follow the local magnetic field lines.

(2) A sufficiently low density plasma would follow the magnetic field immediately. This leads to the following behavior for low density plasmas: for the first 100 m, they are driven radially from the Shuttle by collisions with the neutral exhaust (see Section 1); at about 100 m, they follow the geomagnetic field and consequently move away from the Shuttle at 7 km sec.

(3) A fully ionized exhaust kills the ambient magnetic field until about 10 km from Shuttle, while a very weakly ionized plasma has practically no effects.

5. NEUTRALIZATION OF POLARIZED PLASMA CLOUDS

In the preceding section, it was implicitly assumed that the expanding, highly ionized cloud remained polarized during its evolution. In fact, the polarization state of the cloud is dependent upon the surrounding medium. In the present case, ambient electrons are capable in principle of neutralizing the polarization charge density which shields the electric field in the interior of the cloud. If the polarization can be completely neutralized, the high density cloud will act in the same manner as a low density cloud: it will follow the geomagnetic field lines. The purpose of this section is to inquire about the time required for ambient electrons to neutralize plasma clouds.

A rough estimate of the minimum time required to neutralize a plasma cloud is the time required to fill the cloud with ambient thermal electrons. The cloud certainly cannot be neutralized in much less time. The time rate of change, due to thermal electron flux, of the charge density of a cloud is

$$\frac{dQ}{dt} = -nwa \tag{86}$$

where w is the electron thermal speed and a is the cross sectional area of the cloud along the field. The reason for taking only the area along the field is that the effective electron velocity across the field is the Shuttle velocity, about 7 km/sec. The charge in the cloud is

$$Q = fN \tag{87}$$

where f is the fractional ionization and N is the number of molecules in the cloud. The characteristic time for neutralization is then

$$\tau = -Q/(dQ/dt) \tag{88}$$

$$\approx \frac{fN}{nwa}.$$

The neutralization time is seen to increase with the ionization and depend inversely on the flux of thermal electrons. Taking $N \approx 5 \times 10^{24}$, $n \approx 10^5\,\mathrm{cm}^{-3}$, $w \approx 200\,\mathrm{km/sec}$, and $a \approx r^2$, the neutralization time is seen to be on the order of

$$\tau \approx 2 \times 10^{12} \frac{f}{r^2}\,(\mathrm{cm})\ \mathrm{sec}. \tag{89}$$

A fully ionized cloud cannot be neutralized faster than about $10^{12}/r^2$ sec. For example, if the extent of the cloud is r = 1 km, the neutralization time is 100 sec or more. Neutralization within about 0.01 sec, the time it takes the exhaust to move about 30 m at 3 km/sec requires f to be less than about 10^{-5}. We conclude that weakly ionized clouds, with fractional ionization below perhaps 10^{-5} (and likely one or two orders of magnitude less because of the qualitative nature of the argument), can be neutralized in a satisfactorily short time. Denser clouds continue to travel across the field, while clouds with lower ionization states move with the geomagnetic field almost immediately.

6. DISCUSSION

From the discussion in each section, it is possible to develop a fairly systematic view on the expected large-scale evolution of Shuttle exhaust. Before discussing this picture, however, we should mention that a number of interesting and important topics have been omitted entirely. Among these are the source of the ionization, the way that ionization develops as the cloud expands, processes such as two-stream instabilities associated with streaming of ambient electrons through the ionized cloud, and the possibility of substantial charge separation and the related electric fields associated with the collisions of ions and electrons with the neutral exhaust.

The detailed study of sources of ionization is crucial. The possibilities range from intrinsic ionization of the thermal exhaust to Alfven critical velocity ionization. These may be expected to lead to low-level and high-level ionization, respectively. From what has been said, it may not be possible to determine low levels of ionization based on known properties of the exhaust because of the extreme sensitivity of the ionization level to the temperature of the exhaust and to the presence of contaminants with low ionization potentials. This observation underscores the importance of making direct measurements. In fact, direct measurements of the radiation intensity and perhaps the spectrum of ionized exhaust are crucial to determine whether the ionization level is low or high. Without such measurements, and an accompanying analysis of radiation processes, there can be no certainty of even the approximate nature of the evolution of the cloud. The measurements are needed to guide future investigations, essentially to establish their limits. As an example, suppose that measurements establish that high-level ionization exists in Shuttle exhaust. Then the nature of the investigation would focus on the Schmidt[7] criterion and neutralization of plasma clouds. On the other hand, measurements establishing low-level ionization would turn the investigation toward establishing the temperature of the exhaust and levels of contaminants with low ionization potentials.

With these caveats in mind, let us discuss the picture of the exhaust as it has been developed in the text. The driver of all exhaust phenomena is the momentum and energy of the neutral exhaust. There are two major possibilities for ionization: high level (with critical ionization as a likely source) and low level (with thermal ionization as the likely source). Up to a distance on the order of 50 to 100 m, the evolution of the exhaust is likely to be independent of the ionization level: the ions are dominated by collisions with the thermal exhaust. However, near 100 m, the exhaust becomes collisionless. Past this transition region, neither ions in the exhaust nor ambient particles are strongly affected by collisions. This has two major implications:

(1) Since neutrals cannot penetrate deep inside the exhaust cone inside about 100 m, any collisional phenomena such as chemical reactions, excitation, or ionization by ambients should occur outside 100 m. Because the density of the (neutral) exhaust is larger near 100 m than at greater distances, the intensity of such phenomena will probably be greatest near this distance.

(2) The behavior of ions inside the transition distance will be independent of ionization level inside the transition distance but will depend heavily on the ionization level outside it. Low density ions should show a sharp turn at the transition, where they are swept away at up to 7 km/sec because their motion is dominated by the geomagnetic field. High density ions, on the other hand, should expand radially in the Shuttle frame of reference to a large distance (many kilometers or more) before they can be affected by the field. Between these two limits, there should be a continuum of trajectories. For moderate level ionization, above a fractional ionization of 10^{-5} or so, the neutralization of the polarization charge of the plasma cloud cannot be accomplished rapidly. The consequence of partial neutralization is that the cloud should be partially attached to the magnetic field and be swept away at velocities less than 7 km/sec. An interesting question for future investigation is the nature of the trajectory: Is there still a sharp break near 100 m, or is there a smooth trajectory? The answer presumably depends on the details of the neutralization process, which have not been treated here. The qualitative nature of the paths of low and high density ions is shown in Figure 3.

The behavior of a highly ionized cloud is essentially independent of ambient electric and magnetic fields for a large distance. As such, it should not, for example, show signs of alignment with the magnetic field. On the other hand, a cloud of low density ions can be affected by these fields. It can be accelerated, for example, along the geomagnetic field by relatively low-level parallel electric fields (≈ 0.1 mV/m); it is not known whether such large parallel electric fields actually exist at low altitudes. The geomagnetic mirror force is not strong enough to accelerate ions along the field. As a result, ion clouds cannot be expected to show signs of field alignment. The sole signature of the presence of the ambient fields is likely to be the sharp break of low density ion clouds due to sweeping away of the cloud into the Shuttle wake.

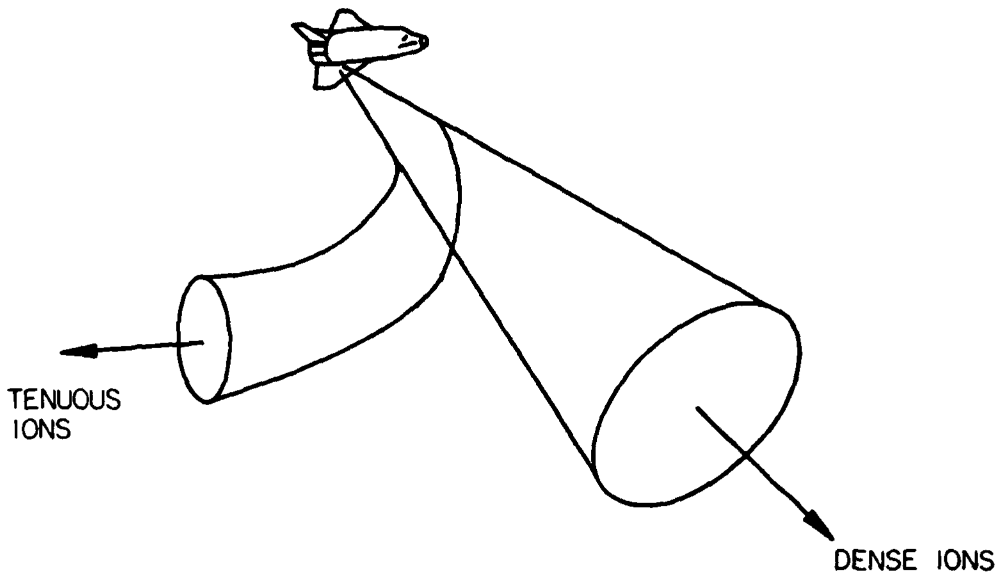

Figure 3. Qualitative Behavior of High Density and Low Density Ions

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